Designing an Effective Vibration-Based Notification Interface for Mobile Phones

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ABSTRACT

We conducted an experiment to understand how mobile phone users perceive the urgency of ten simple vibration alerts that were created from four basic signals: short on, short off, long on, and long off. The short and long signals correspond to 200 ms and 600 ms, respectively. To convey the level of urgency of notifications and help users prioritize them, the design of mobile phone vibration alerts should consider that the gap length preceding or succeeding a signal, the number of gaps in the vibration pattern, and the vibration's duration affect an alert's perceived level of urgency. Our study specifically shows that shorter gap lengths between vibrations (200 ms vs. 600 ms), a vibration pattern with one gap instead of two, and shorter vibration all contribute to making the user perceive the alert as more urgent.

Author Keywords

Vibration patterns; mobile phone; perceived urgency; notifications; alerts.

ACM Classification Keywords

H.5.3 [Information Interfaces and Presentation]: Group and Organization Interfaces – Computer-supported cooperative work, Synchronous interaction, Collaborative computing.

INTRODUCTION

Notification interfaces that inform users about the status and activities of others without overwhelming or distracting them are a key concern in computer-supported cooperative work (CSCW). This is reflected in dozens of studies on awareness and notification that were presented at the CSCW conference [2]. Among the different types of notification interface, the ones that use vibration are particularly important.

Vibration is an essential component of the mobile phone notification system today. It is useful especially when the user's auditory and visual modalities are occupied or limited due to social and environmental factors. While the vibration alert was typically used for signalling incoming calls and text messages in feature phones, in today's smartphone, it can represent a wide array of notifications from numerous sources, ranging from games, location-based services, and communication-related applications. However, the same general vibration alert is used for all notifications, which could otherwise have sounded differently if the smartphone were not in silent mode.

In many previous projects, vibrotactile urgency perception was enhanced by increasing the range of tactile modality at the fingertips. These involved employing a range of amplitude [13], frequency [7, 13, 15], vibration direction [7], gap length, intensity [14], as well as multiple actuators [5]; or trying to perceive salient tactile cues by attaching the device to seated participants' waists [12].

Although many of these innovative solutions were successful, they were tested on delicate tactioception nerves in the fingertips and areas of the hand where idle mobile phones are less likely to be located [5, 7, 13, 15], or used extra vibrators [5, 14] or modified mobile phones [7, 13, 15]. These make the studies impractical and less realistic for mobile phones and smartphones that were manufactured in the past few years.

As such, users are still unable to distinguish the priority of incoming messages from the vibration alert generated by unmodified mobile phones (i.e., phones without any custom hardware modification). We designed a practical vibration notification interface for an unmodified mobile phone by:

a) Eliminating all features that are not currently supported by today's mobile phone, including frequency, amplitude, and intensity. This also excludes custom-made vibrators as they require hardware modifications.

b) Testing the phone in the trouser pocket of a user's pants instead of in other locations because this is where mobile phones are more commonly carried [8].

Three controllable factors affect the perceived urgency of basic vibration alerts in these types of phone: gap length, number of gaps, and vibration length.

A previous study by White [14] considered gap length a factor. This study used only a single gap length (with gap length vs. without) and was conducted using a customized adjustable tactile belt display system that is no longer available in current mobile phones. Thus, the results are not as relevant to today's mobile phone users. Our study uses short and long gap lengths.

One plausible way to alleviate tactile modality crowding is by assigning a level of urgency for the incoming alert through the vibration signal itself. Vibration alerts can be interpreted and associated with different objects and concepts [9], as well as encoded with three urgency levels according to the designer's preferences [4]. Users have to undergo an active learning process to interpret their meaning. Little is known on how mobile phone users naturally interpret a vibration alert's sense of urgency. Therefore, we aim to understand the perceived urgency of these vibration alerts through an empirical study on basic vibration patterns, and to answer the following questions:

1. How many levels of urgency can users reliably associate with simple vibration patterns?
2. What are the underlying factors that make users perceive certain vibration patterns as more urgent than others?
3. How does the combination of these factors amplify or diminish the degree of perceived urgency?

Future design of mobile phones vibration alerts can leverage our findings to convey its degree of urgency and help its users to understand and prioritise the incoming alerts.

Note that the study of Qian et al. [12] also uses the length of the vibration signal and the length of the gaps as parameters for vibration pattern design, but with a different focus. Their study tries to understand the differences between two types of vibration pattern design (static vs. dynamic) and which combination pair can yield the most distinguishing effect while our focus is to not only understand the differences, but also to construct an ordered list of distinguishable patterns and understand what is the limit in terms of number of patterns human can reliably distinguish.

Pilot Study

In a real world scenario, environmental noise is a constant distraction. It can easily interfere with sounds that accompany a vibration alert, making it difficult to determine their effect on the user's perception. To avoid such complications, we eliminated the potential influence of audio by providing an audio mask.

We carried out a pilot study on six participants with ages ranging from 21 to 25 years to determine the type of audible mask that should be used and to find out the appropriate lengths for short and long signals. We found that pink noise is more effective in masking audible cues than Brownian noise [3]. And, as determined in previous research [10], we confirmed that the appropriate lengths for short and long signals are 200 ms and 600 ms, respectively.

Pattern Design

A vibration pattern is defined as an arrangement of the simplest repeatable alternating sequence of an actuator's on and off state, with specific lengths (short and long) assigned to each state. We limited the variable of short to 200 ms and long to 600 ms, without any median values due to its susceptibility to detection errors. As shown in a previous vibrotactile study [3], participants could differentiate vibrotactile signals with extreme values well but were less able to do so with median values. We used four basic types of signal to form distinguishable vibration patterns: short on, short off, long on, and long off.

In order to produce unique repeatable sequences, an equal number of on and off signals must be alternated in arrangements that do not replicate any other sequence. A pair of short and long on-off signals forms four unique patterns, labelled 1 to 4 in Figure 1. Two pairs of such signals form additional 16 patterns, of which only six are unique. These unique patterns are labelled 5 to 10. An initial test on four undergraduate students confirmed that the ten patterns were distinguishable while those that were comprised of three pairs of on-off signals were hard to distinguish. Thus, we did not consider patterns consisting of three or more pairs of on-off signals in the study.

EXPERIMENT 1

The purpose of the first experiment is to determine how many levels of urgency users can distinguish and how the urgency of each of the ten vibration patterns is ranked.

White [14] simply presented all the vibration patterns sequentially, then asked users to rank them. However, this approach is infeasible due to the limitation of human short-term memory: remembering and comparing more than two patterns presented in sequential order is difficult. Therefore, we adopted pairwise comparison, in which users are only required to compare two patterns at a time. The ranking of all ten patterns was then derived from the aggregated comparison results of the individual pairs.

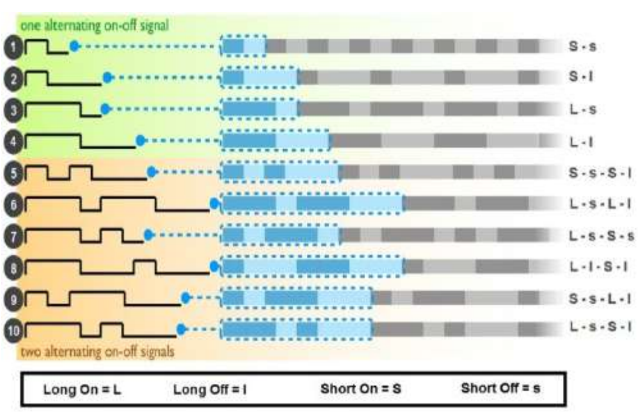

Figure 1. All possible distinguishable permutations of the four basic types of signal and the vibration patterns they produce, based on one and two pairs of 200 ms (short) or 600 ms (long) on-off signals. Each pattern is repeated (played) for a total duration of 4,500 ms.

Apparatus

We programmed an Android application to present the 45 comparisons in five rounds and installed it on a NexusOne smartphone running Android 2.1. The smartphone weighs 130 g and measures 119 x 59.8 x 11.5 mm. It contains one vibrating micro-motor that operates on 1–2 VDC with a weight of .05 oz, a dimension of .5 in long, and a diameter of .188 in [6].

Participants

Sixteen participants (10 male and 6 female) with ages ranging from 19 to 25 years from four different nationalities (mean: 23, SD: 1.83) took part in this experiment.

Procedure

At the beginning of the experiment, participants were briefed and asked to try the ten vibration patterns while adjusting the volume of the audible mask. We then placed the smartphone inside their right pants pocket, allowing the phone to rest naturally on the thigh.

During the experiment, the 45 pairs of vibration patterns were presented in a reduced Latin square to counterbalance learning and order effects. This prevents participants from extrapolating new judgments from previous ones. Each pairwise comparison was presented to the participants by playing the first pattern for 4.5 seconds, following it with a 1.5-second gap, and playing the second pattern for 4.5 seconds. The participants were then asked to compare the perceived urgency of the two patterns by selecting the most appropriate answer out of the following:

1: the first pattern is more urgent,
2: the second pattern is more urgent,
1≅ 2: the first and second patterns are comparable, and
Repeat: perform the comparison again.

The first three are equivalent to the options in a 3-point Likert scale. We choose the simpler 3-point scale because previous research [1] showed that having more options to select from may confuse participants. A post-experiment questionnaire asked the participants to describe the characteristics of the vibration patterns.

Results of Experiment 1

We analyzed the pairwise comparisons of the 45 comparison results we collected from each participant, and from that data ranked the ten vibration patterns in ten levels of urgency (Fig. 2). For instance, if Patterns 1, 2, and 3 show that:

- Pattern 1 is more urgent than Pattern 2,
- The urgency levels of Patterns 1 and 3 are comparable,
- Pattern 3 is more urgent than Pattern 2,

Patterns 1 and 3 are ranked Level 1 and Pattern 2 ranked Level 2.

Not all results were consistent. For instance, a participant judged the urgency levels of pattern pair 4-7 to be comparable and pattern pair 7-9 to be comparable. Logically, the urgency level of Patterns 4 and 9 should be comparable but the participant perceived their urgency levels to be different from each other. However, this inconsistency was observed only two times during the entire experiment and the participants were not made aware of it. We corrected it by simply repeating the comparisons for the pattern pairs in question until the results were consistent.

Figure 2 summarizes each participant's ranking of the ten vibration patterns. While there are individual differences, a number of common trends can also be observed. It was obvious which patterns occupied the extreme ends of the spectrum: all participants ranked Pattern 2 as the least urgent while almost all of them (14 out of 16) ranked Pattern 1 as the most urgent. The ranking of patterns in the middle range is less consistent.

DISCUSSION

The ranking of these patterns gives us a basis for discussing the reasons behind the differences in perceived urgency and the factors that contributed to these differences.

Descriptions of Individual Signals

We asked participants to describe the characteristics of the vibration patterns, then classified similar comments and adjectives into four groups: short on, long on, short off, and long off. Short on is often described as a firm and sharp vibration while long on is described as steady. Short off gives some participants the feeling of being hurried while the feeling long off imparts is slow and relaxed. These qualities describe each of the four basic signals that we used for creating the vibration patterns in this study.

On-Off Signal Pairs

We classified the results into two groups based on the number of consecutive on-off signals in each pattern's basic design.

	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8
L1	6,3	1	1	1	1	1	1	1
L2	4	3, 6	3, 6	3, 6	6, 3, 9	3, 6	3,6, 9	3, 6
L3	1	9	9	7, 9	4, 7	9	4, 7	7, 9
L4	7	4	7	4	5	7	5	4
L5	9	7	4	5	8, 10	4	8, 10	5
L6	5	5	10	8, 10	2	8	2	8, 10
L7	8,10	8, 10	5, 8	2		5, 10		2
L8	2	2	2			2		
L9								
L10								

	P 9	P 10	P 11	P 12	P 13	P 14	P 15	P 16
L1	1	1	1	1	1	3,6,9	1	1
L2	3	3, 6	3,6,7,9	3, 6	3,4,6,7,9	1	3,6, 9	3
L3	6	9	4	4,7, 9	5	4	4, 7	6
L4	9	7	5	5, 8, 10	10	7	5,8, 10	9
L5	7	4	8,10	2	8	5,8, 10	2	4
L6	4	5	2		2	2		7
L7	5	8, 10						5
L8	10	2						8
L9	8							10
L10	2							2

Figure 2. Ranking results for the 16 participants. P1-P16 represents the participant IDs. The level of urgency is listed in descending order with Level 1 (L1) being the most urgent and Level 10 (L10) being the least urgent.

After ranking the ten vibration patterns, we computed the dissimilarity matrix by squared Euclidean distance. To derive an aggregated ranking from all the participants' ordinal data, we applied a hierarchical clustering algorithm based on the dissimilarity matrix calculation, as this method is recommended for clustering ordinal data [18]. Figure 3 shows the various clustering results and their ranking.

3 Clusters	4 Clusters	5 Clusters
L 1: Pattern 1	L 1: Pattern 1	L 1: Pattern 1
L 2: Patterns 3,4,5,6,7,8,9,10	L 2: Patterns 3,4,6,7,9	L 2 : Patterns 3,6
L 3: Pattern 2	L 3: Patterns 5,8,10	L 3 : Patterns 4,7,9
	L 4: Pattern 2	L 4 : Patterns 5,8,10
		L 5 : Pattern 2

6 Clusters	7 Clusters	8 Clusters
L 1: Pattern 1	L 1: Pattern 1	L 1: Pattern 1
L 2 : Patterns 3,6	L 2 : Patterns 3,6	L 2 : Patterns 3, 6
L 3 : Patterns 4,7,9	L 3 : Patterns 7,9	L 3 : Pattern 9
L 4 : Pattern 5	L 4 : Pattern 4	L 4 : Pattern 7
L 5 : Patterns 8,10	L 5 : Pattern 5	L 5 : Pattern 4
L 6 : Pattern 2	L 6 : Patterns 8, 10	L 6 : Pattern 5
	L 7 : Pattern 2	L 7 : Patterns 8, 10
		L 8: Pattern 2

Figure 3. Classifying the 10 vibration patterns into various clusters based on dissimilarity matrix calculation. (L stands for level of urgency)

Patterns 1 through 4 are in the one on-off signal pair group. Patterns 5 through 10 are in the two on-off signal pair group. These groups shall be referred to as "one on-off" and "two on-off" respectively.

There was an extreme variation in results in the one on-off group because Patterns 1 and 2 were distinguishable in all the different clusters. A more direct cause-effect relationship was observed in this group because the single on and off signal limits attenuating effects on multivariate signal length.

On the other hand, variation in results in the two on-off group was milder. This could be due to the presence of two on-off signals, which attenuate the effects of each on or off signal. In addition, combinations of two on signals and two off signals increased the pattern's complexity and further moved its perceived urgency towards a neutral point. As a result, about half of the participants were undecided when asked to compare two patterns from the two on-off group. The majority of participants wanted the interviewer to play the pattern pair again.

It is worth noting that—as seen in the results of the post-experiment questionnaire—most of the participants were able to describe, through comparisons of the patterns within the one on-off group, the signal characteristics of the patterns in that group. They were also able to associate simpler patterns, i.e., those belonging to the one on-off group, with the appropriate level of urgency.

Characteristics of Vibration Patterns' Signals

Similarities among some of the ten vibration patterns were grouped based on their level of urgency and the characteristics of their signals (Fig. 4). These were marked accordingly for further analysis. In comparing each pattern's signal characteristics, we found similarities that potentially contributed to some patterns being perceived as more urgent than others. This can be observed particularly among the patterns in the one on-off group.

Vibration Patterns	1	3	6	9	7	4	5	8	10	2
One Short Off	X	X								
One Long Off						X				X
Two Short Off					X					
Two Long Off								X		
Two Mixed Off			X	X			X		X	
One Short On	X									X
One Long On		X				X				
Two Short On							X			
Two Long On			X							
Two Mixed On				X	X			X	X	

Figure 4. A table of signal characteristics of vibration Patterns 1 to 10.

• Given the same gap length between vibrations, a pattern that contains short gap(s) was perceived to be more urgent than those with longer gap(s).

• Given the same number of gaps, a pattern with one gap was perceived to be more urgent than those with two gaps.

• Given the same length of vibration, a pattern with shorter vibration was perceived to be more urgent than those with longer vibration.

Factors that Influence the Perceived Level of Urgency

Three underlying factors contribute to users' perceived urgency of vibration alerts: gap length is the strongest factor, followed by number of gaps, and finally vibration length.

Experiment results and qualitative analysis reveal that the short on signal is highly susceptible to varying perceptions of its level of urgency, depending on the length of the gaps that precede and succeed it. A gap length of 200 ms between short on signals heighten perceived urgency because the short and sharp pulse is delivered in a stronger manner. On the other hand, a 600 ms gap length preceding or succeeding a short on signal diminishes its strength, making the pulse feel weaker.

White [14] showed that pulses with different intensities that have no gaps between them were perceived as more urgent than those with long gaps. This is reflected in the results of Patterns 1 and 2, which ranked as most urgent and least urgent, respectively. In comparison, the long on signal has a steady attribute that makes it less susceptible to fluctuations caused by gaps surrounding it. Therefore, the discrepancy between Patterns 3 and 4 is minimal.

EXPERIMENT 2

In Experiment 1, simple vibration patterns were clustered and ranked according to their perceived urgency, and factors that contributed to differences in perceived urgency were identified. Figure 3 shows how the 10 patterns can be grouped into different clusters (from three clusters to eight). However, how many different levels of urgency can a user reliably distinguish when receiving random, isolated vibration notification? If a smartphone uses N, which represents the number of clusters, how large can N be before a user can no longer reliably indentify each vibration pattern's corresponding urgency level?

In Experiment 2, we asked participants to identify the urgency level of individual vibration notifications. From Experiment 1, we know that the range for N is somewhere between 3 and 10. The initial candidates of our investigation were N=4 clusters, N=5 clusters, and N=6 clusters. The patterns from each N were selected from their corresponding levels of urgency: Patterns 1, 2, 10, and 6 were selected for N=4 clusters; Patterns 1, 2, 4, 10, and 6 were selected for N=5 clusters; and patterns 1, 2, 4, 10, 6 and 5 were selected for N=6 clusters.

Participants

Twelve new participants (six male and six female) with ages ranging from 19 to 25 years took part in this experiment.

Procedure

The participants were briefed and were asked to try each vibration pattern while adjusting the volume of the audible mask. The experiment was divided into three parts: in the first part, the participants were asked to rank four vibration patterns. In the second part, they were asked to rank five, and in the third part they were asked to rank six. The order of presentation was counterbalanced using a Latin Square.

For each part, the participants were given the total number of urgency levels that they will use for ranking, as well as the number of times the patterns will be played in random order. In the first part, for instance, the participants went through four trials to rank four patterns according to four levels of urgency. For each trial, the participant was asked to indicate the level by holding up a small placard with the appropriate sign. The interviewer recorded the response before playing the next set of patterns. The three parts of the experiment were separated by two-minute breaks.

Results of Experiment 2

We performed a one-way repeated measure ANOVA for the single factor, number of urgency levels on the dependent measure, accuracy of recognition. Accuracy of recognition was calculated using the number of correct recognition trials divided by the total number of trials, the value is shown as a percentage

The result showed that there is a significant main effect on the number of urgency levels for recognition accuracy ($F_{2, 22} = 26.78$, $p < .01$). Pairwise t-tests with a Bonferroni correction showed that the recognition accuracy of four urgency levels (95.8%) is not significantly different from the recognition accuracy of five urgency levels (81.7%, $p = .082$), but both of them are significantly higher than the recognition accuracy of six urgency levels (57%, $p < .01$). We found that 11 out of the 12 participants could clearly distinguish and rank all four vibration patterns into four levels correctly. Seven out of 12 participants could clearly distinguish and rank all five vibration patterns into five levels correctly. However, none of them could rank six vibration patterns into six levels correctly.

In all three parts of the experiment, all the participants were able to correctly identify and rank Pattern 1 as the most urgent pattern and Pattern 2 as the least urgent. This shows that the number of vibration patterns and levels of urgency that participants can distinguish is between four and five.

Based on the findings, we developed an Android application that can assign different levels of urgency to different contacts' incoming calls or messages. As demonstrated in the accompanying video, participants can distinguish the level of urgency of an incoming call or message even without an audio alert.

CONCLUSION

The perceived urgency of simple vibration alerts is affected by three primary factors. The basic signals that were used to create the ten vibration patterns had characteristics—short on, short off, long on, and long off—the combination of which had attenuating effects particularly in more complex patterns of two or more on-off signal pairs. Thus, to effectively impart the level of urgency, the vibration pattern design should be at its simplest form with the least number of on-off signal pairs.

The study investigated vibration patterns made of one and two on-off signal pairs with two distinct lengths. We found that users can reliably distinguish at least four levels of urgency based on the simple design of our vibration alerts. We implemented a system-level application so that notifications are more personalized, for instance by tailoring vibration alerts of incoming calls based on the user's communication history as well as application usage trends. More complex patterns can be explored in future studies to discover possible associations with more complex concepts.

A better understanding of perceived urgency associated with vibration patterns can help future designers create notification interfaces that effectively convey a vibration alert's level of urgency, help users understand and prioritize incoming alerts, and alleviate information overload. It is our hope that our findings contribute to more effective computer-supported cooperative work on awareness and notification.

Finally, such understanding can also contribute to the research of eyes-free interaction, as the vibration signals can complement existing eyes-free interaction techniques primarily based on auditory feedback (e.g., earPod [17]) to come up with more effective multi-modal interfaces. The resulting interfaces will have more expressive power to serve the variety of needs behind eyes-free interactions [16].

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REFERENCES
1. Crawford, G., Williams, C. The Analysis of Subjective Judgment Matrices, Rand Corporation (1985)
2. Cadiz, JJ., Venolia, G.D., Jancke, G., Gupta, A. Designing and deploying an information awareness interface. In *Proc. CSCW 2002*, ACM (2002), 314-323
3. Enriquez, M., MacLean, K., Chita, C. Haptic phonemes: basic building blocks of haptic communication. In *Proc. Multimodal Interfaces* 2006, ACM (2006), 302-309.
4. Hoggan E., Brewster S. New parameters for tacton design. In *Proc. CHI 2007 extended abstracts*, ACM (2007), 2417-2422
5. Hoggan, E, Anwar, S., Brewster, S. Mobile multi-actuator tactile displays. *Haptic and Audio Interaction Design* (2007), 22–33.
6. OEM Google Nexus One Vibrating Motor, http://www.globaldirectparts.com/OEM-Google- Nexus-One-Vibrating-Motor-p/htc736660.htm
7. Hwang, J., Hwang, W. Vibration perception and excitatory direction for haptic devices. *Journal of Intelligent Manufacturing* (2010), 1-11
8. Ichikawa, F., Chipchase, J., Grignani, R. Where's the Phone? A Study of Mobile Phone Location in Public Spaces. In *Proc. IEEE Mobility Conference* (2005), 797 - 804.
9. Kaaresoja, T. Mobile phone using tactile icons. *US Patent App 20,020/177* (2002)*,471*
10. Kaaresoja, T., Linjama, J. Perception of Short Tactile Pulses Generated by a Vibration Motor in a Mobile Phone. In *Proc. World Haptics (2005),* 471–472
11. Miranda, E. Improving subjective estimates using paired comparisons. *IEEE Software* 18,1 (2001), 87 - 91
12. Qian, H., Kuber, R., Sears, A. Towards Identifying Distinguishable Tactons for Use with Mobile Devices. In *Proc*. *ASSETS (2009)*, 257-258
13. Ryu J., Jung J., Choi S. Perceived magnitudes of vibrations transmitted through mobile device. In *Proc. HAPTICS 2008*, IEEE (2008), 139-140.
14. White, T. The Perceived Urgency of Tactile Patterns. Human Research and Engineering Directorate, Army Research Laboratory. ARL-TR-5557 (2011)
15. Yao H. Y., Grant D., and Cruz-Hernandez J. M. Perceived vibration strength in mobile devices: The effect of weight and frequency. In *Proc. IEEE transactions on haptics 2009*, IEEE (2009), 56-62
16. Yi, B., Cao, X., Fjeld, M. Zhao, S. Exploring User Motivations for Eyes-free Interaction on Mobile Devices. In *Proc. CHI 2012*, ACM (2012), 2789–2792
17. Zhao S., Dragicevic, P., Chignell, M.H., Balakrishnan, R., Baudisch, P. earPod: Eyes-free Menu Selection with Touch Input and Reactive Audio Feedback. In *Proc CHI 2007*, ACM (2007), 1395-1404
18. Žiberna, A., Kejžar, N.,Golob, P. A comparison of different approaches to hierarchical clustering of ordinal data, Metodološki zvezki, Vol 1,1 (2004), 57-73